Symmetric WIMP dark matter and Baryogenesis

To appear soon...

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Facts

- Baryon Asymmetry of the Universe (BAU)
  $Y_B \equiv n_B / s \simeq 8.5 \times 10^{-11}$

- Baryonic matter abundance
  $\Omega_B h^2 = 0.02260 \pm 0.00053$

- Dark matter (DM) abundance
  $\Omega_{DM} h^2 = 0.1123 \pm 0.0035$

- $\Omega_{DM} / \Omega_B \sim 5 \Rightarrow$ common origin?

Asymmetric Dark Matter

hep-ph/0410114, hep-ph/0510079, arXiv: 0807.4313, arXiv: 0901.4117, arXiv: 0909.2035, arXiv: 0909.5499, arXiv: 0911.4463, arXiv: 1005.1655, arXiv: 1008.1997, arXiv: 1008.2399, arXiv: 1008.2487, arXiv: 1009. 0983, arXiv: 1009.2690, arXiv: 1009.3159, arXiv: 1011.1286, arXiv: 1012.1341, arXiv: 1101.4936, arXiv: 1104.1429, arXiv: 1104.5548, arXiv: 1106.4319, arXiv: 1106.4320, arXiv: 1106.4834, arXiv: 1108.3967, arXiv: 1201.2699, arXiv: 1202.0283, arXiv: 1203.1247, arXiv: 1204.5752, arXiv: 1205.0673, arXiv: 1205.2844 ...

- Relate the asymmetries in the dark and visible sectors
- Non-trivial structure of dark sector

Are there attempts to make a connection between symmetric DM and BAU?

- Baryomorphosis McDonald, 1009.3227 and 1108.4653

- Dark Matter Assimilation
  D'Eramo, Fei, Thaler, 1111.5615

- WIMPy Baryogenesis
  Cui, Randall, Shuve, 1112.2704

A WIMPy baryogenesis miracle

Cui, Randall, Shuve, 1112.2704

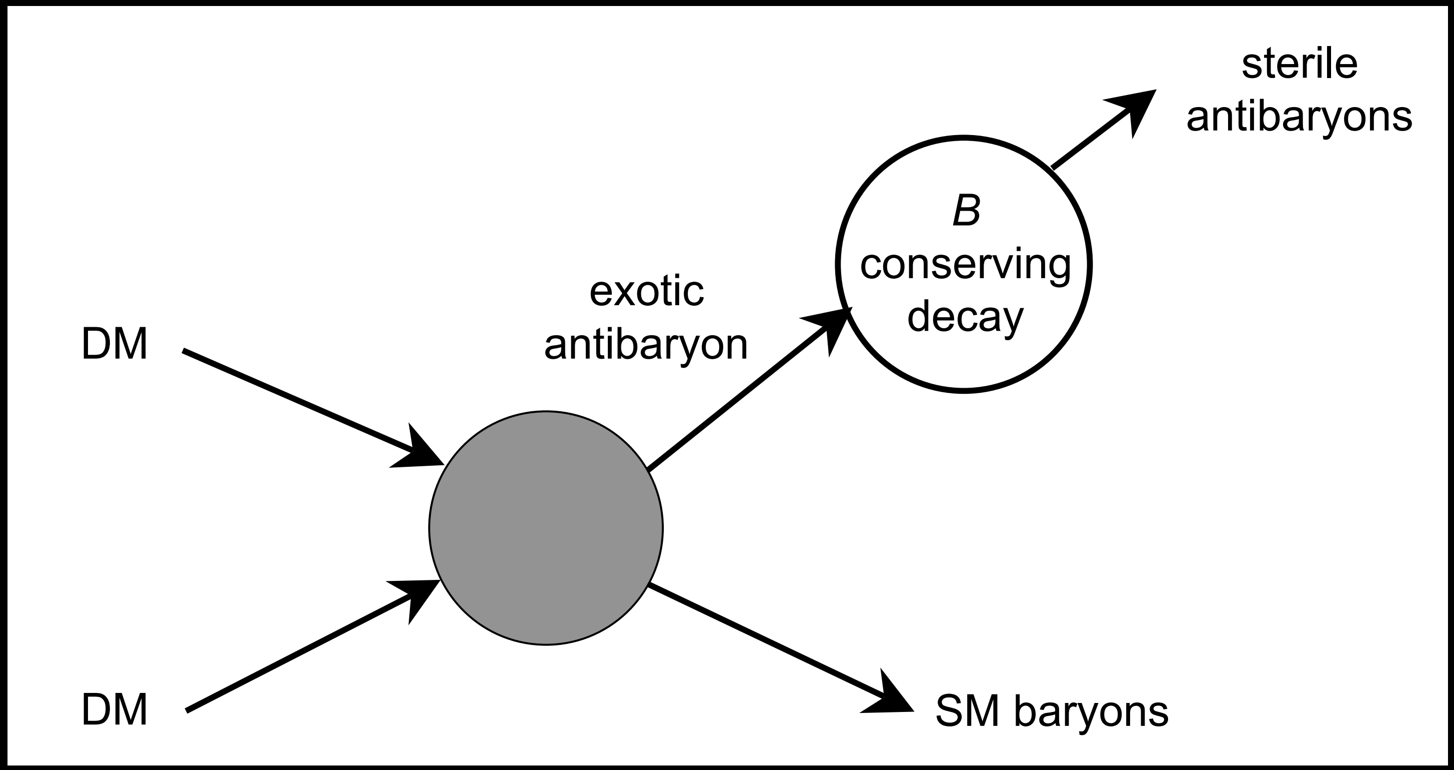
Cui, Randall, Shuve, 1112.2704

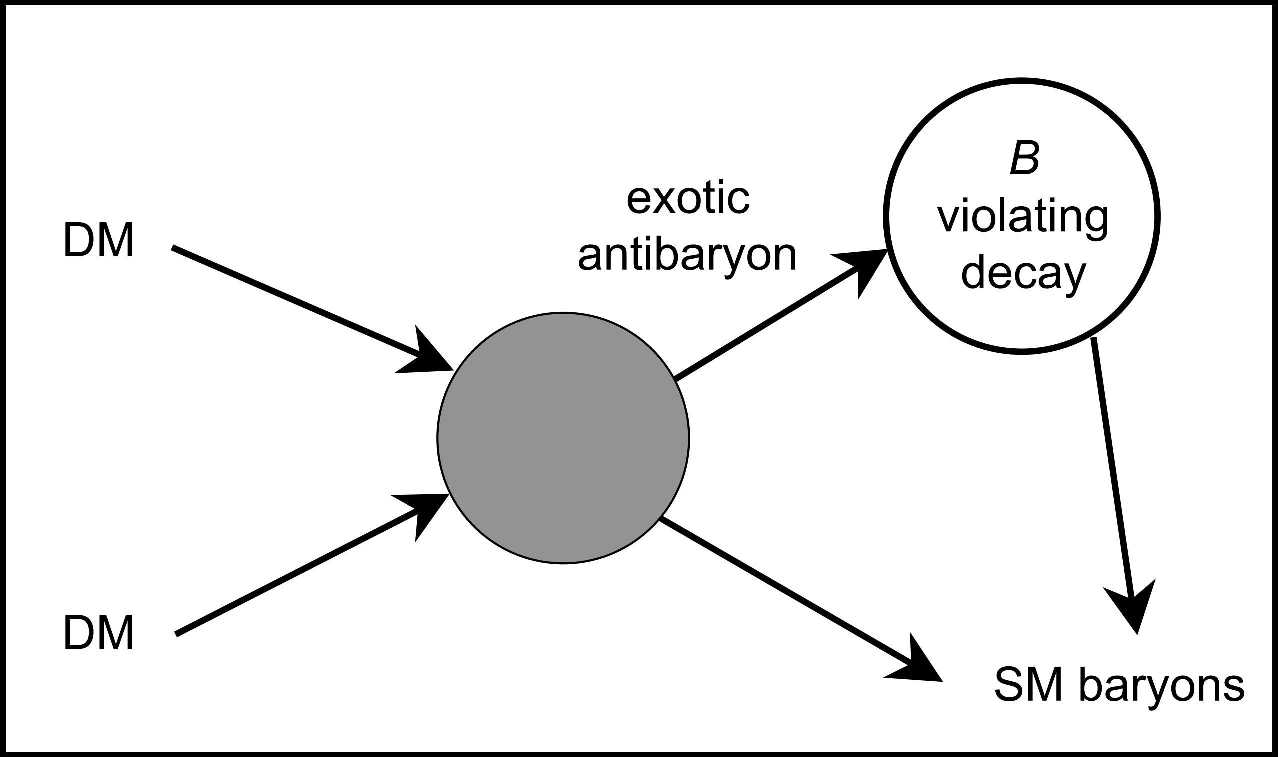
Two miracles in one framework!

1. WIMP miracle
   weak-scale DM, thermal relic abundance

2. WIMPy baryogenesis miracle
   DM annihilation generates the baryon asymmetry

Cui, Randall, Shuve 1112.2704





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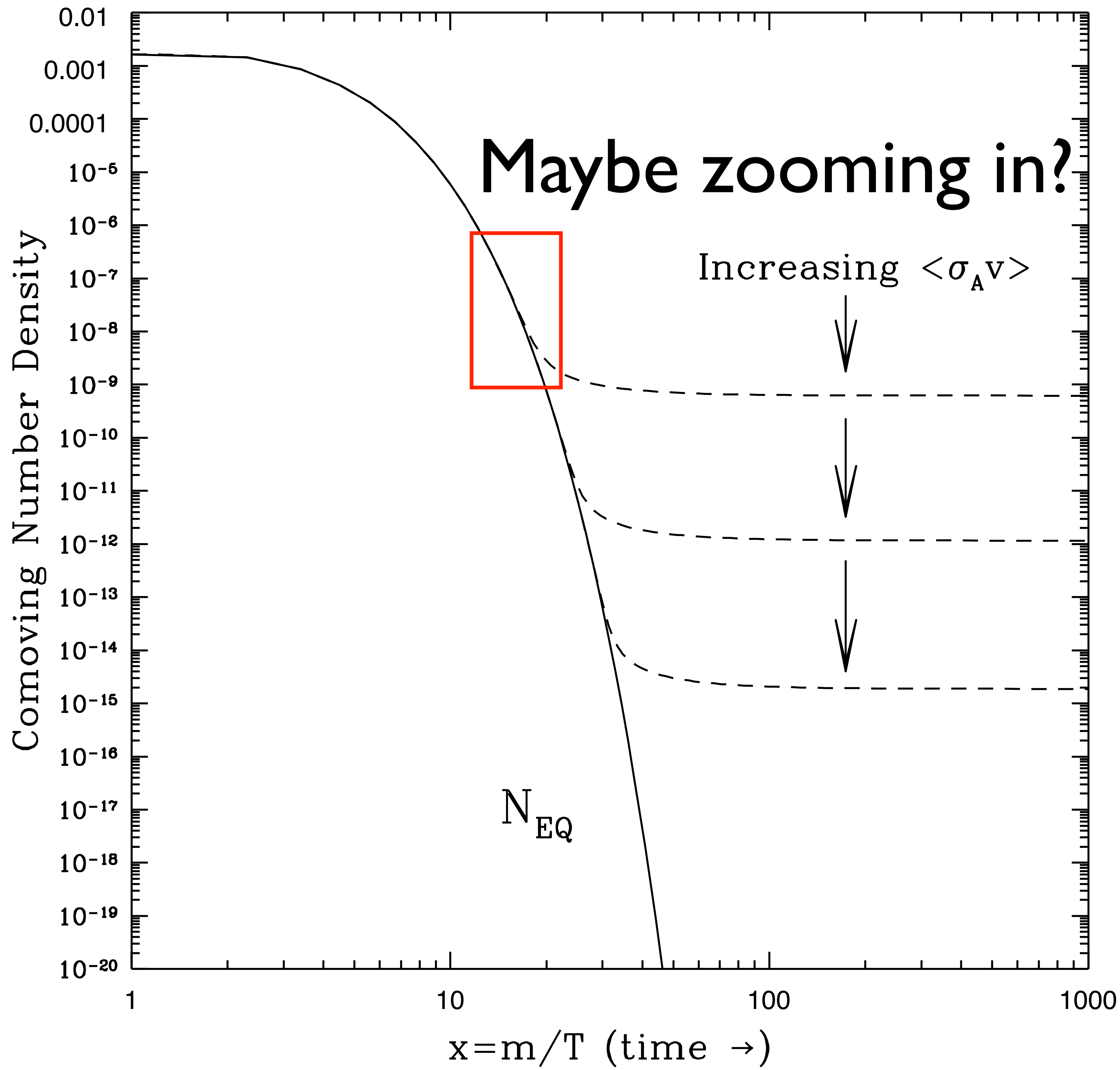
Sakharov conditions

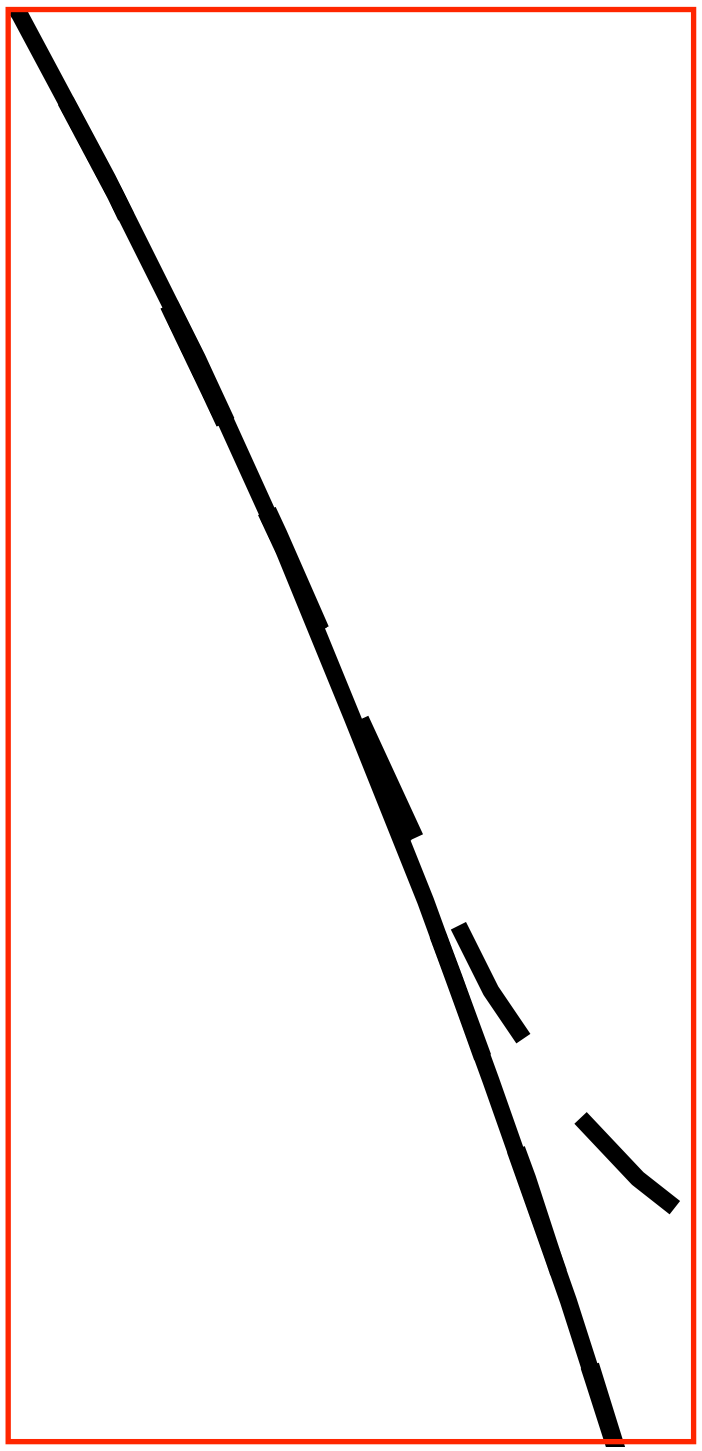
√ 1. B-number violation

√ 2. CP violation

3. Out of thermal equilibrium

Departure from thermal equilibrium?





Don't be fooled!!

The departure from equilibrium is very small and not visible by eye on these plots, but it's good enough for our purpose.

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Sakharov conditions

√ 1. B-number violation

√ 2. CP violation

√ 3. Out of thermal equilibrium

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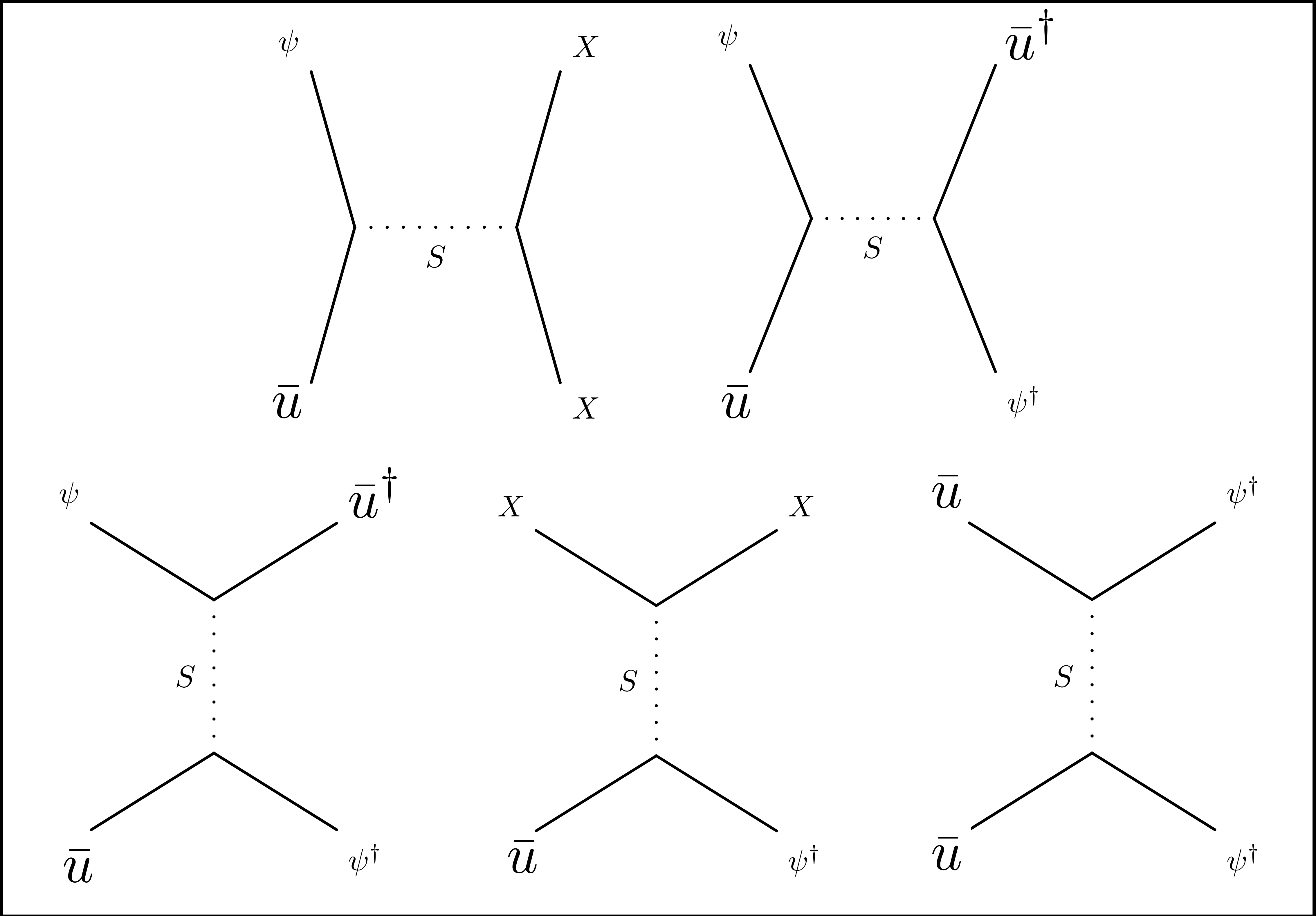
Washout processes



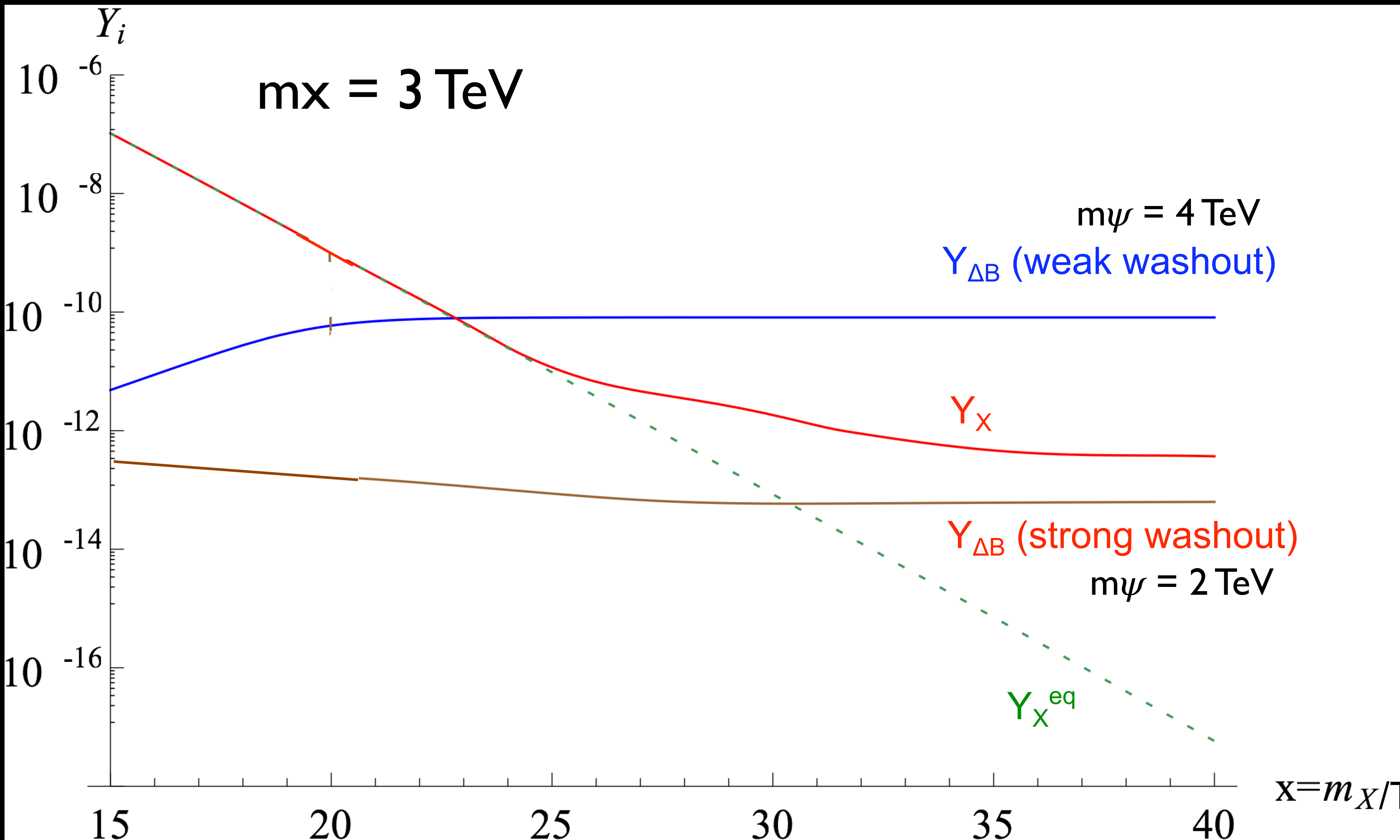
Central result

"If washout processes freeze out before WIMP freeze-out, then a large baryon asymmetry may accumulate, and its final value is proportional to the WIMP abundance at the time that washout becomes inefficient."

$$\Rightarrow \qquad m_\psi \gtrsim m_x$$

Also, $m_\psi < 2m_x$ so that the annihilation
DM + DM → ψ + quark
is kinematically allowed.

Cui, Randall, Shuve 1112.2704



Our work

Fundamental ingredients for WIMPy baryogenesis

Dark matter

Exotic heavy quark

Sterile majorana fermion

	$SU(3)_c$	$SU(2)_L$	$Q_{U(1)_y}$	$Q_{U(1)_B}$	$\mathbb{Z}_4$
X	1	1	0	0	$+i$
$\bar{X}$	1	1	0	0	$-i$
ψ	3	1	$+2/3$	$+1/3$	$+1$
$\bar{\psi}$	$\bar{3}$	1	$-2/3$	$-1/3$	$+1$
n	1	1	0	0 or $+1$	$+1$
$\bar{u}$	$\bar{3}$	1	$-2/3$	$-1/3$	-1
$\bar{d}$	$\bar{3}$	1	$+1/3$	$-1/3$	-1

$$\psi \to \bar{d}\bar{d}n$$

The discrete symmetry

- Start with a $\mathbb{Z}_n$

$$Q_X = \exp\left(\frac{2\pi i}{n} q_X\right), \quad Q_\psi = \exp\left(\frac{2\pi i}{n} q_\psi\right), \quad Q_{\bar{u}} = \exp\left(\frac{2\pi i}{n} q_{\bar{u}}\right)$$

- Require DM stability → $q_X \neq 0$

- Forbid proton decay → $q_{\text{quarks}} \neq 0, \quad q_{\text{leptons}} = 0$

- Avoid dangerous decays of ψ → $q_\psi \neq q_{\text{quarks}}, \quad q_\psi = 0$

- Allow the operators $(XX)(\psi\bar{u})$ AND $(XX)(\psi^\dagger\bar{u}^\dagger)$ at the same time → $2q_X + q_{\bar{u}} = 0 \,(\text{mod } n), \quad 2q_X - q_{\bar{u}} = 0 \,(\text{mod } n),$

- Solution $q_X = n/4,$ $\quad q_{\bar{u}} = n/2 \quad \rightarrow \quad n = 4k \quad \rightarrow \quad \mathbb{Z}_4$

Complex charge → Dirac fermion

The effective lagrangian

$$L_{eff} = \frac{1}{\Lambda^2} \sum_i \lambda_i^2 \mathcal{O}_i$$ dim 6 operators, i = 1, ... ,20

e.g. $\mathcal{O}_1 = (XX)(\psi \bar{u})$ and so on ...

For comparison:

$$L = L_{kin} + L_{mass} - \frac{i}{2} \lambda_{X\alpha} S_\alpha (XX + \bar{X}\bar{X}) + i\lambda_{B\alpha} S_\alpha \bar{u}\psi$$

Cui, Randall, Shuve 1112.2704

What's new?

- We have a total of 20 dim-6 operators (not all of which are important).
- They allow for the possibility of
  - t-channel DM annihilation into quark + exotic quark (on top of the s-channel);
  - DM annihilation into quark + antiquark (that does not contribute to the asymmetry);
  - tree-level processes for direct detection.
- We can study a class of models that extends and generalizes the one given in Cui, Randall, Shuve 1112.2704

Our goal is

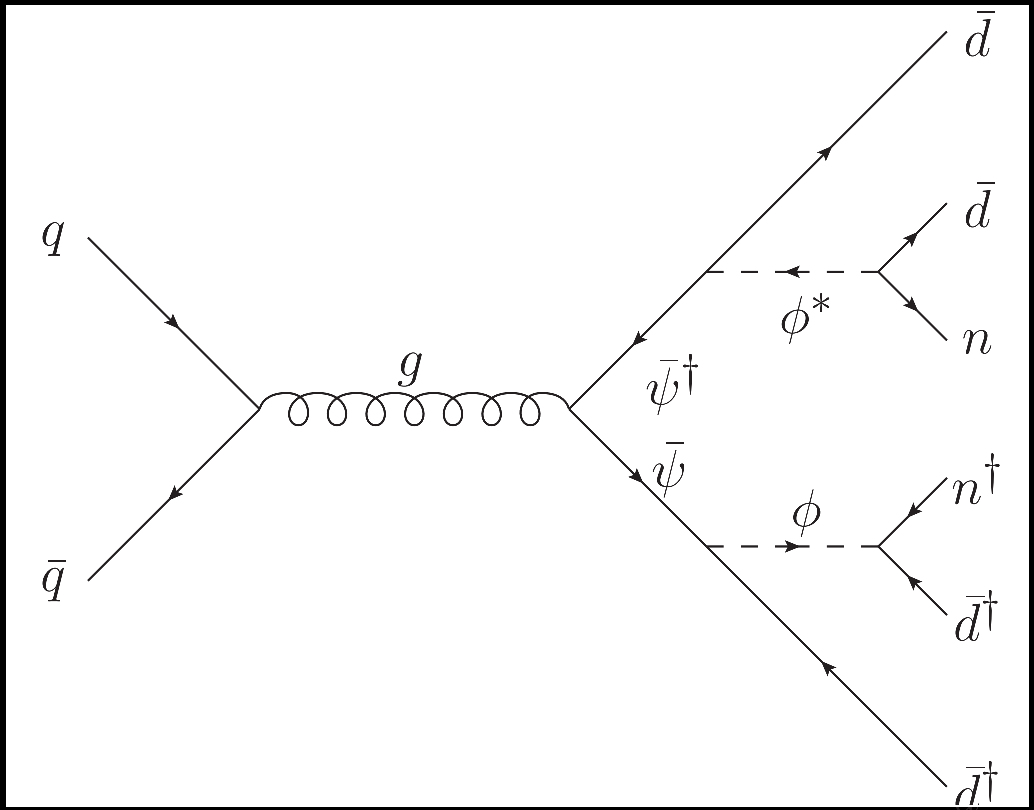
to constrain these models, after reasonable, simplifying assumptions, using

- LHC data
- cosmological data (Boltzmann eqs. study)
- direct detection data

↓

understand if regions of the parameter space survive where the models work

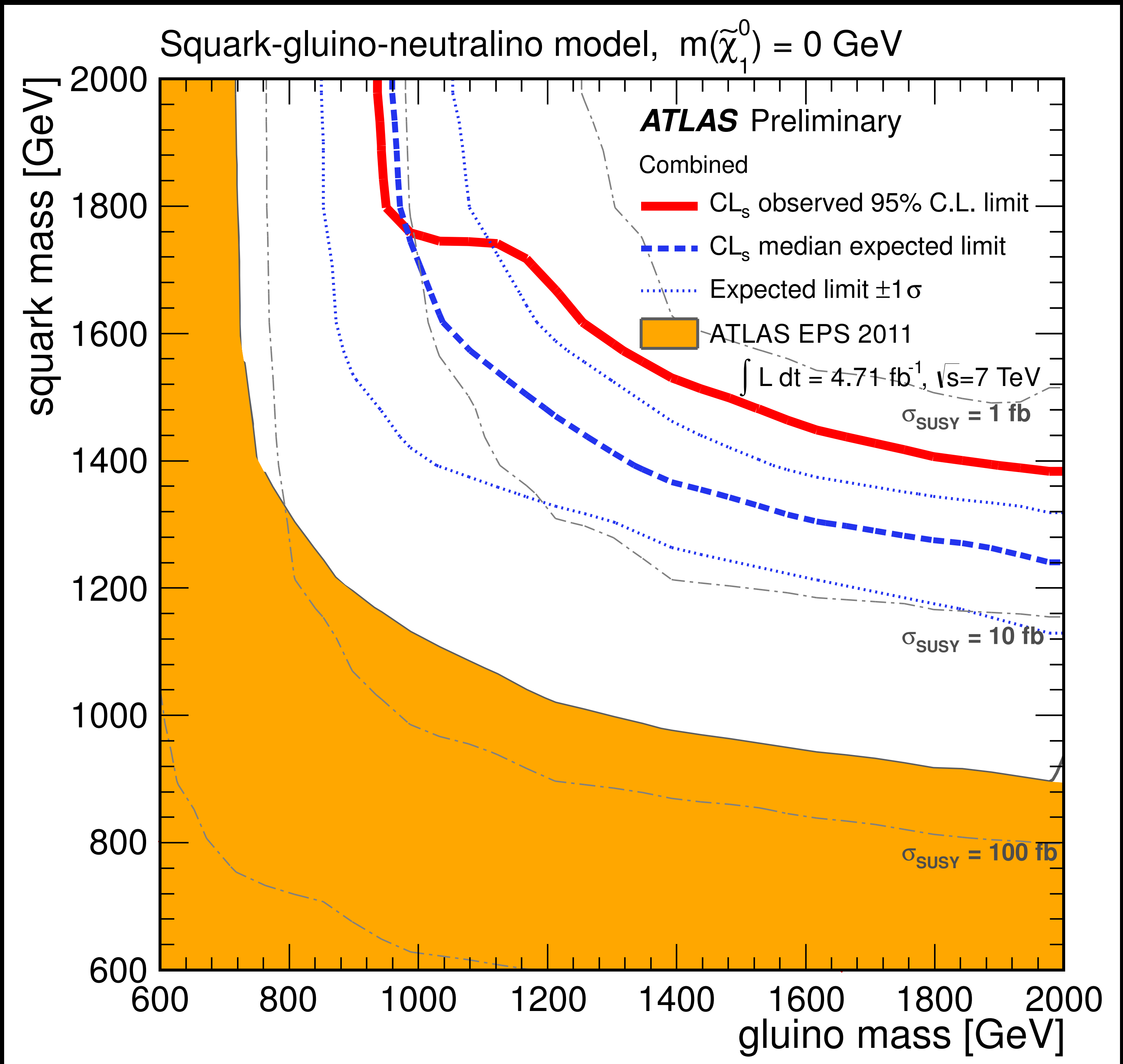
LHC bounds



ATLAS NOTE

ATLAS-CONF-2012-033

March 11, 2012



$$m_\psi \gtrsim 800 \text{ GeV}$$

$$\Rightarrow \; m_x \gtrsim 400 \text{ GeV}$$

$$L_{eff} = \frac{1}{\Lambda^2} \sum_i \lambda_i^2 \mathcal{O}_i$$

Reasonable, simplifying assumptions

λ_s coupling for all s-channel DM annihilation (into quark + exotic quark) operators

λ_t coupling for all t-channel DM annihilation (into quark + exotic quark) operators

λ_{WO} coupling for all washout operators

Validity of EFT approach

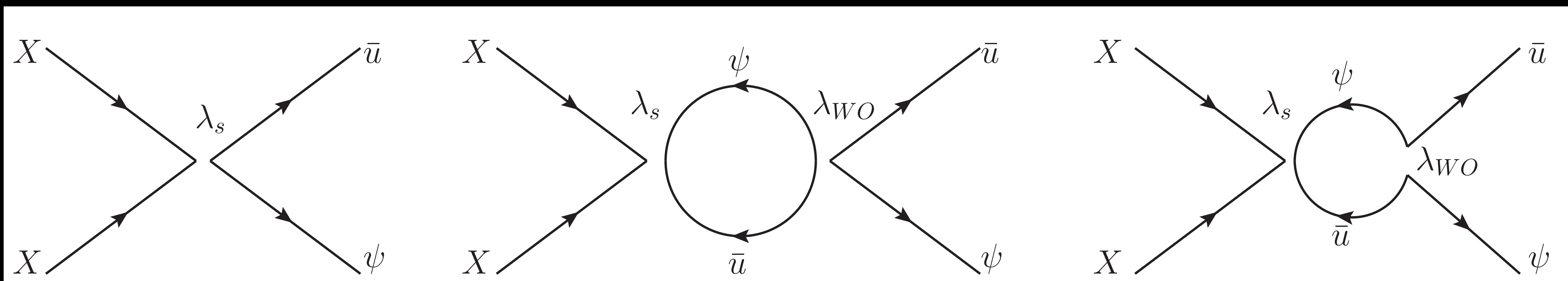
$$\frac{\lambda_i}{\Lambda} k_{max} < 1 \qquad k_{max} \sim 100 \text{ GeV} \qquad \frac{\lambda_i}{\Lambda} < (100 \text{ GeV})^{-1}$$

Λ = 10 TeV → $\lambda_i < 100$

Cosmological bounds

Generation of the asymmetry

$$\epsilon = \frac{\sigma(XX\to\psi\bar{u}) + \sigma(\bar{X}\bar{X}\to\psi\bar{u}) - \sigma(XX\to\psi^\dagger\bar{u}^\dagger) - \sigma(\bar{X}\bar{X}\to\psi^\dagger\bar{u}^\dagger)}{\sigma(XX\to\psi\bar{u}) + \sigma(\bar{X}\bar{X}\to\psi\bar{u}) + \sigma(XX\to\psi^\dagger\bar{u}^\dagger) + \sigma(\bar{X}\bar{X}\to\psi^\dagger\bar{u}^\dagger)}$$

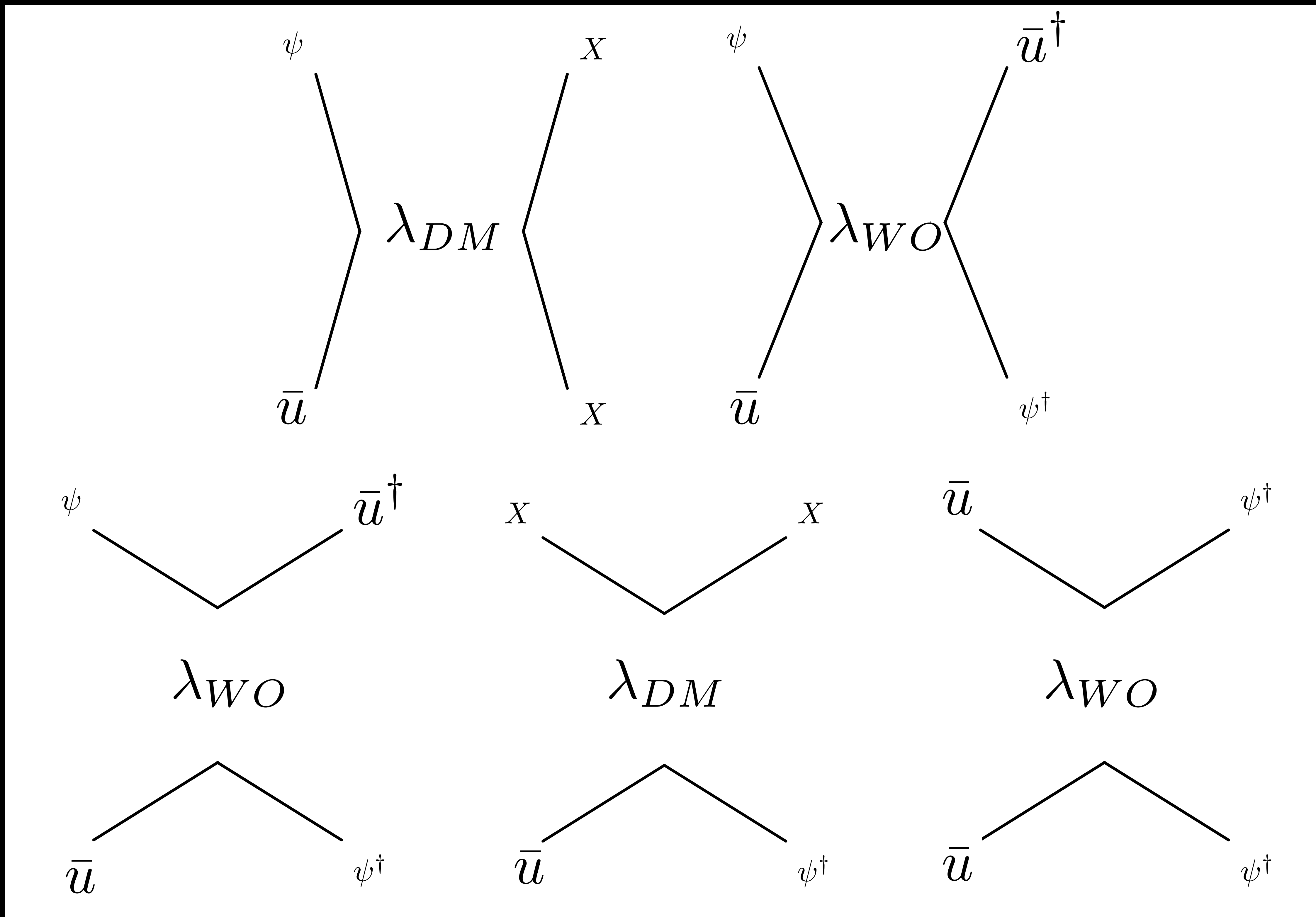


$$\epsilon \propto \frac{\mathrm{Im}(\lambda_{WO}^2)}{\Lambda^2}\frac{(s-m_\psi^2)^2}{16\pi s}$$

The washout coupling has to be complex

$$\lambda_{WO} = |\lambda_{WO}|e^{i\delta}$$

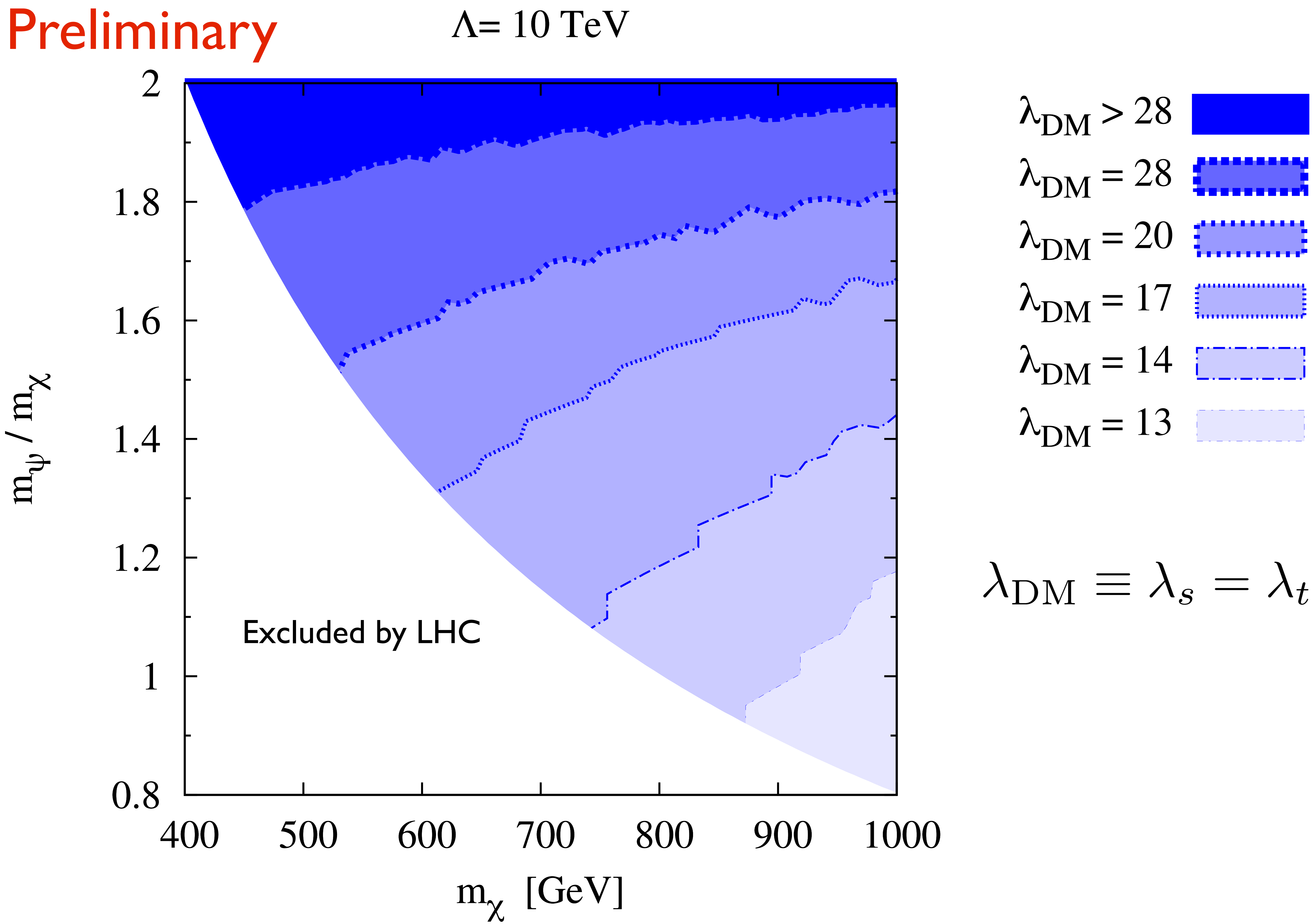
Washout



ψ
X
ψ
$\bar{u}^\dagger$
λ_{DM}
λ_{WO}
$\bar{u}$
X
$\bar{u}$
$\psi^\dagger$
ψ
$\bar{u}^\dagger$
X
X
$\bar{u}$
$\psi^\dagger$
λ_{WO}
λ_{DM}
λ_{WO}
$\bar{u}$
$\psi^\dagger$
$\bar{u}$
$\psi^\dagger$
$\bar{u}$
$\psi^\dagger$

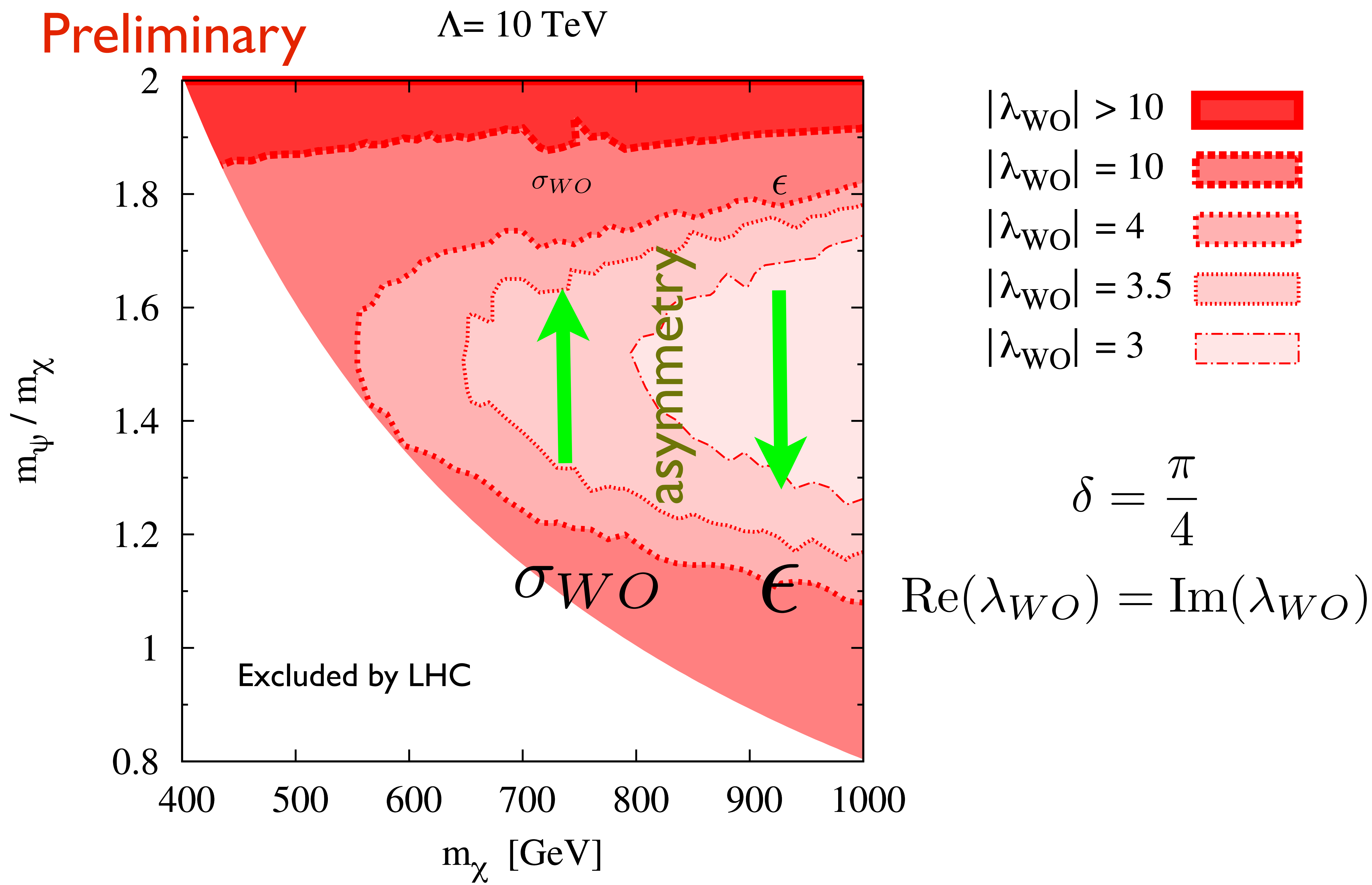
DM relic density

Preliminary



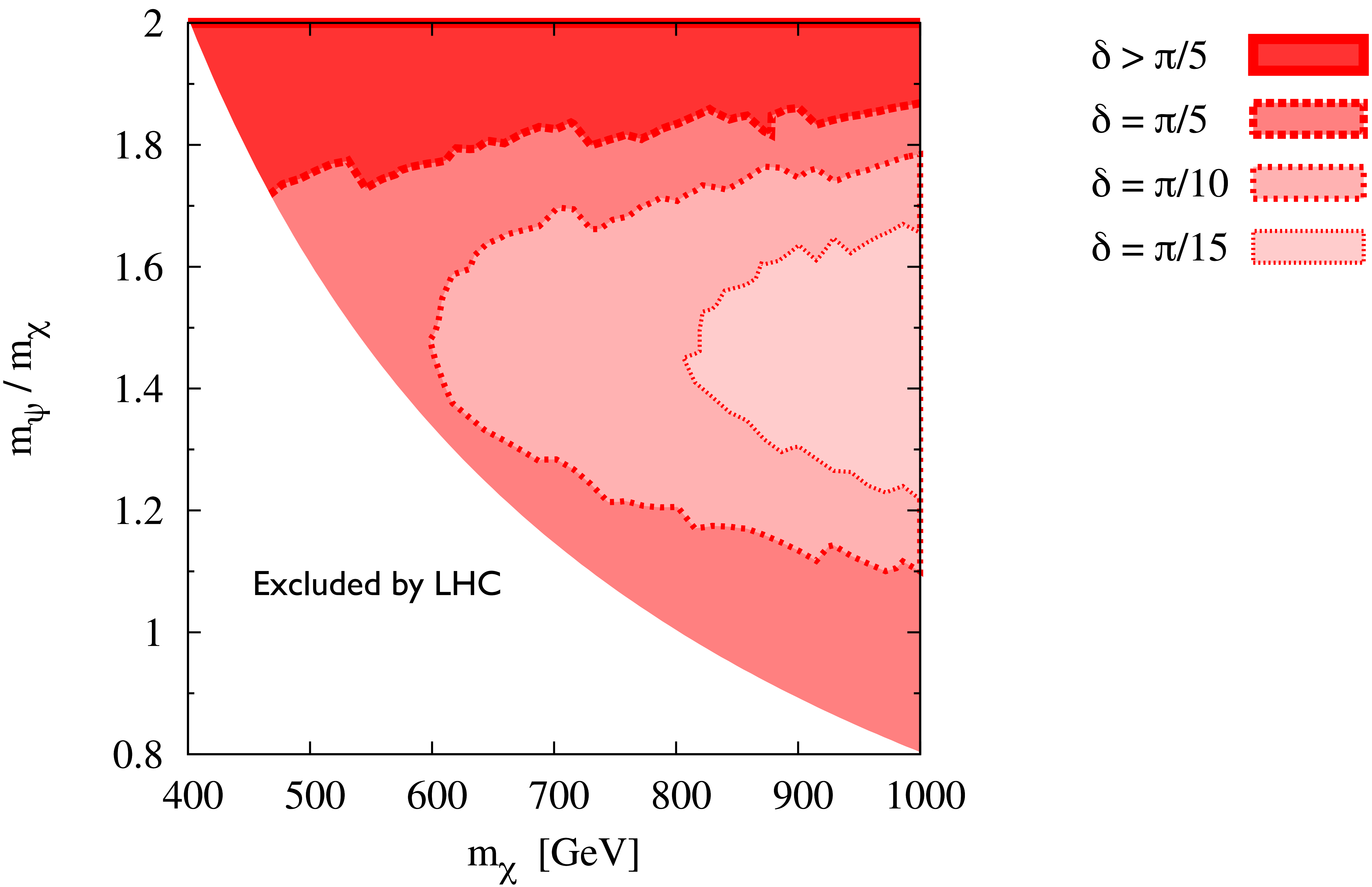
$$\lambda_{\rm DM} \equiv \lambda_s = \lambda_t$$

DM relic density + BAU



DM relic density + BAU

Preliminary $\Lambda = 10$ TeV, $|\lambda_{WO}| = 5$



Direct detection bounds

$$\frac{1}{\Lambda^2}(\lambda_7^2(X\bar{u})(X^\dagger\bar{u}^\dagger) + \lambda_8^2(\bar{X}\bar{u})(\bar{X}^\dagger\bar{u}^\dagger) + \mathrm{h.c.})$$

Translated into 4-component-spinor notation

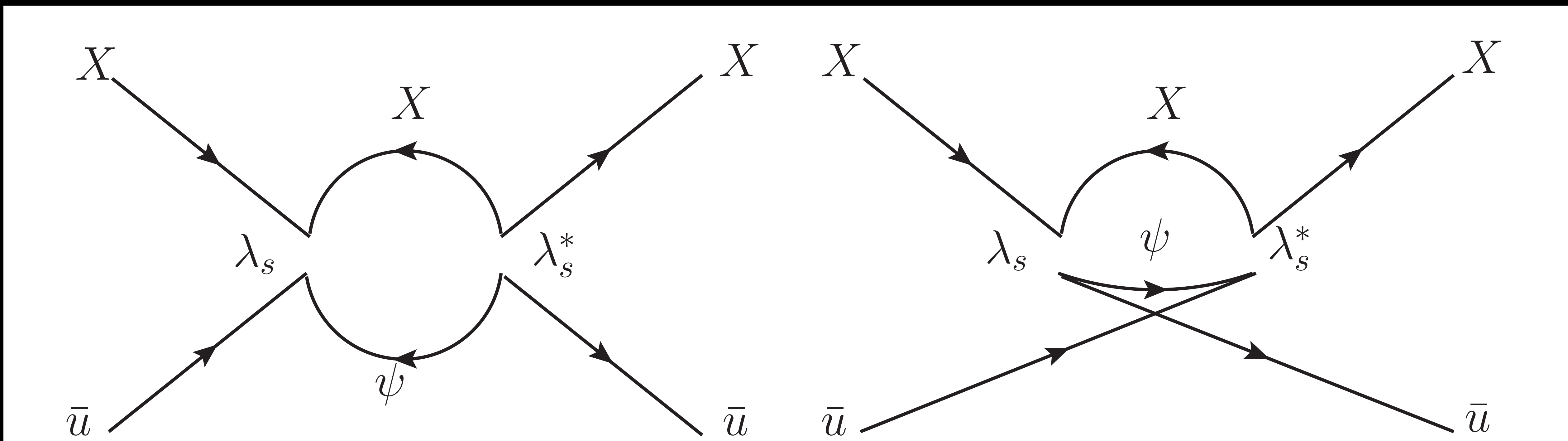
$$\frac{\lambda_8^2-\lambda_7^2}{4\Lambda^2}(\bar{\chi}\gamma^\mu\chi\bar{U}\gamma_\mu U + \bar{\chi}\gamma^\mu\chi\bar{U}\gamma_\mu\gamma_5 U) + \frac{\lambda_8^2+\lambda_7^2}{4\Lambda^2}(\bar{\chi}\gamma^\mu\gamma_5\chi\bar{U}\gamma_\mu U + \bar{\chi}\gamma^\mu\gamma_5\chi\bar{U}\gamma_\mu\gamma_5 U)$$

These operators contribute to
1. DM annihilation into a pair of quarks and
2. to SI and SD direct detection

(2) constrains the couplings 7 & 8 to be somewhat small, which is good anyway for (1), given that we want the annihilation into q + exotic q to dominate over q + qbar.

Direct detection bounds

Can we constrain λ_s and λ_t looking at one-loop contributions to direct detection?



The 2 diagrams cancel!!

Similar story for t-channel operators.

NO BOUNDS FROM DIRECT DETECTION

Summary

- WIMPy baryogenesis is an interesting mechanism that relates the baryon asymmetry to the WIMP thermal relic density
- For the models we considered the mechanism works in a good portion of the parameter space
- Think about different, maybe even simpler models that implement the mechanism?